

# Double beta decay versus cosmology: Majorana CP phases and nuclear matrix elements

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## Abstract

We discuss the relation between the absolute neutrino mass scale, the effective mass measured in neutrinoless double beta decay, and the Majorana CP phases. Emphasis is placed on estimating the upper bound on the nuclear matrix element entering calculations of the double beta decay half life. Consequently, one of the Majorana CP phases can be constrained when combining the claimed evidence for neutrinoless double beta decay with the neutrino mass bound from cosmology.

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Over the past years much effort has been invested to probe leptonic mixing with increasing accuracy, and, in fact, a unique picture is evolving from the precise measurements of neutrino oscillation probabilities. For a full construction of the mixing matrix, however, knowledge about CP violating phases is necessary.

To describe leptonic mixing one can always work in a basis where the charged lepton Yukawa matrix is diagonal. In this case the neutrino mass matrix  $m^\nu$  can be written in the flavor basis as

$$m^\nu = U^* m^{\text{diag}} U^\dagger, \quad (1)$$

with  $m^{\text{diag}} = \text{diag}(m_1, m_2, m_3)$ , and the Maki-Nakagawa-Sakata (MNS) matrix  $U$ , which contains three mixing angles and one CP violating Dirac phase. The determination of the mixing angles is subject to neutrino oscillation experiments, as is (at least in principle) the determination of the Dirac phase - the leptonic analogue of the CKM phase in the quark sector. Three of the mixing angles can be identified with the maximal, large and small observables measured in atmospheric, solar and reactor neutrino oscillations, respectively [1]. Important information on the Dirac phase can be expected from a combination of future long-baseline experiments [2], and ultimately, from a neutrino factory [3].

If the neutrino is of Majorana type, two more phases enter, though. The determination of these Majorana phases is, in fact, the most challenging task in the reconstruction of the fundamental parameters of the Standard Model particle content. In general,  $U$  can be written as

$$U = V \cdot \text{diag}(1, e^{i\phi_{12}/2}, e^{i\phi_{23}/2}), \quad (2)$$

where  $V$  is parametrized in the standard CKM form,

$$V = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (3)$$

and  $\phi_{ij}$  are the Majorana phases under discussion. A viable possibility to obtain information on the Majorana phases is to compare measurements of the absolute neutrino masses  $m_i$  with the elements of the neutrino mass matrix  $m^\nu$  in the flavor basis. While absolute neutrino masses are most stringently constrained from cosmology, only the  $ee$  element of  $m^\nu$  is experimentally accessible, being the effective mass  $m_{ee}$  measured in neutrinoless double beta decay. Several works have discussed the relations of  $m_{ee}$ , absolute neutrino masses and Majorana phases [4]. In [5] it was pointed out that one could restrict the Majorana Phase  $\phi_{12}$  by using the recently claimed evidence for neutrinoless double beta decay [6] and

the cosmological neutrino mass bound derived by the WMAP collaboration [7], if a certain nuclear matrix element (NME) calculation [8] is assumed. An important issue is, however, the uncertainty in the neutrino mass determination within the double beta decay framework due to systematical limitations in such NME calculations. In this work we focus on what can be learned about Majorana phases from recent double beta decay and cosmological structure formation data, in view of an upper bound on the NME. In the following, we first review the claimed evidence for neutrinoless double beta decay and discuss the upper bound on the NME. Finally, we compare the lower bounds on  $m_{ee}$  obtained with the upper bounds on neutrino masses from cosmology.

The half life of neutrinoless double beta decay is given by

$$[T_{1/2}^{0\nu\beta\beta}]^{-1} = \left| \frac{m_{ee}}{m_e} \right|^2 G_1^{(0\nu)} |\mathcal{M}^{(0\nu)}|^2, \quad (4)$$

where  $m_e$  denotes the electron rest mass,  $G_1^{(0\nu)}$  is a phase space factor, and the NME is given by  $\mathcal{M}^{(0\nu)} = \mathcal{M}_{GT} - \mathcal{M}_F$ , being a combination of Gamov-Teller and Fermi transitions. The neutrinoless double beta decay is sensitive to the  $ee$  element of the mass matrix  $m^\nu$  (1) in flavor space,

$$\begin{aligned} |m_{ee}| &= \left| \sum_i |V_{ei}|^2 e^{i\phi_i} m_i \right| \\ &= \left| m_1 |V_{e1}|^2 + \sqrt{m_1^2 + \Delta m_{12}^2} |V_{e2}|^2 e^{i\phi_{12}} + \sqrt{m_1^2 + \Delta m_{12}^2 \pm \Delta m_{23}^2} |V_{e3}|^2 e^{i\phi_{23}} \right|. \end{aligned} \quad (5)$$

Here the mass eigenstates are expressed as  $m_1$ ,  $m_2 = \sqrt{m_1^2 + \Delta m_{12}^2}$ ,  $m_3 = \sqrt{m_2^2 \pm \Delta m_{23}^2}$ , where the plus (minus) sign applies in the normal (inverted) mass hierarchy case.

From the Chooz and Palo Verde experiments we know that  $|V_{e3}^2| \ll |V_{e1}^2|, |V_{e2}^2|$ . Moreover, in the quasi-degenerate mass range explored by the present experiments, one has  $m_1^2 \gg \Delta m_{12}^2, \Delta m_{23}^2$ . Employing the above approximations we arrive at a very simplified expression for  $m_{ee}$  (see, e.g. [9]):

$$|m_{ee}|^2 \approx \left[ 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\phi_{12}}{2}\right) \right] m_1^2, \quad (6)$$

illustrating that  $m_{ee}$  is mostly sensitive to  $\theta_{12}$  and  $\phi_{12}$ .

In Figs. 1 and 2,  $m_1^2/|m_{ee}|^2$  is shown as a function of  $\phi_{12}$ , using the exact relation (5). The full colored/shaded region indicates the allowed range according to the combination of  $2\sigma$  (Fig. 1) and  $3\sigma$  (Fig. 2) limits on the neutrino oscillation observables  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ ,  $\Delta m_{12}^2$ ,  $\Delta m_{23}^2$  [1]. The remaining Majorana phase  $\phi_{23}$  is varied in its full range,  $\phi_{23} \in [0, 2\pi]$ . The dark/red bands correspond to a fixed maximal (upper band), best-fit (middle) and minimal

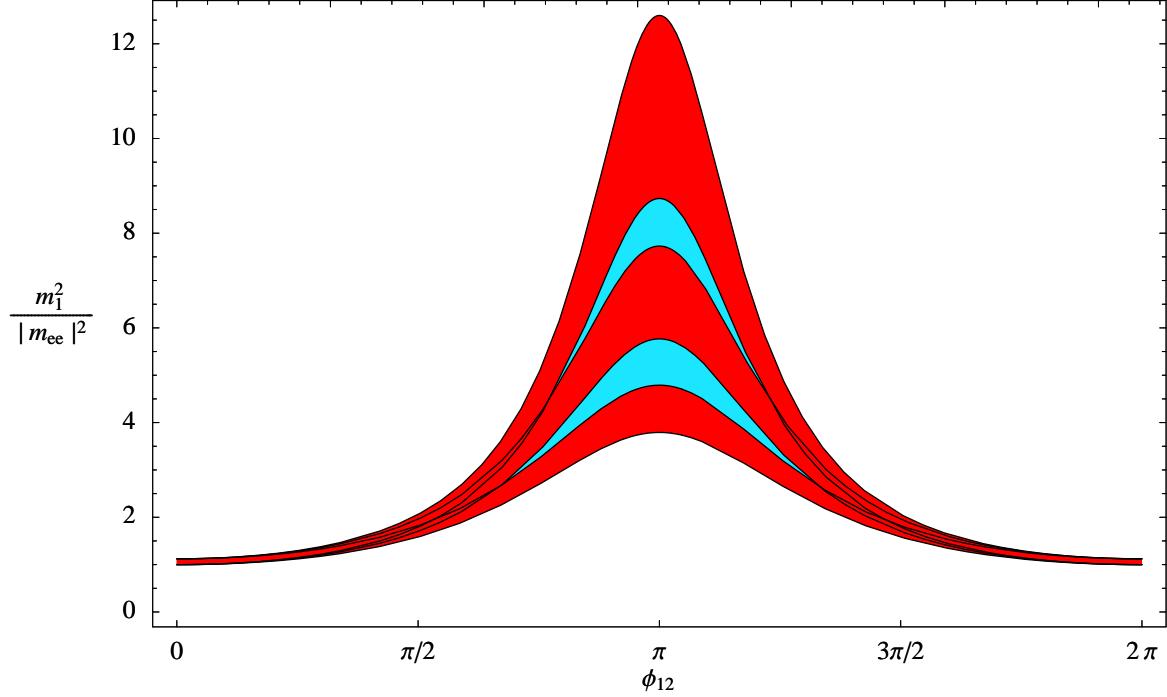


Figure 1:  $m_1^2/|m_{ee}|^2$  as a function of the Majorana phase  $\phi_{12}$ . The full colored region is the allowed range defined by present  $2\sigma$  limits on  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ ,  $\Delta m_{12}^2$ ,  $\Delta m_{23}^2$ . The dark/red bands correspond to a fixed maximal (upper band), best-fit (middle) and minimal (lower) value for  $\theta_{12}$ , varying all other parameters. The second Majorana phase  $\phi_{23}$  has been varied in the full range  $[0, 2\pi]$ .

(lower) value for  $\theta_{12}$ , varying all other parameters. The minimum values for  $m_1^2/|m_{ee}|^2$  at  $\phi_{12} = \pi$  are at 3.81 and 3.23 for  $2\sigma$  and  $3\sigma$  oscillation limits, respectively. Thus, if the experimental values for  $m_1^2/|m_{ee}|^2$  turn out to be smaller, a Majorana CP phase  $\phi_{12} = \pi$  is excluded. If, finally  $m_1^2/|m_{ee}|^2 < 1$ , the bound from unitarity of the MNS matrix  $U$  would be violated, resulting in the conclusion, that either the limit on  $m_1$  or the limit on  $|m_{ee}|$  is not applicable.

Recently, a new publication of data of the Heidelberg-Moscow experiment [10], searching for the double beta decay of  $^{76}\text{Ge}$ , has appeared. In this work the authors have analyzed the data taken in the period 1990-2003, and applied a new energy calibration, which increased the previous claim for evidence [6] to  $4.2\sigma$  statistical significance. The allowed range corresponds to [11]

$$|m_{ee}| = \xi \cdot (0.39 - 0.49 \text{ eV}) \quad [1\sigma], \quad (7)$$

$$|m_{ee}| = \xi \cdot (0.32 - 0.54 \text{ eV}) \quad [2\sigma], \quad (8)$$

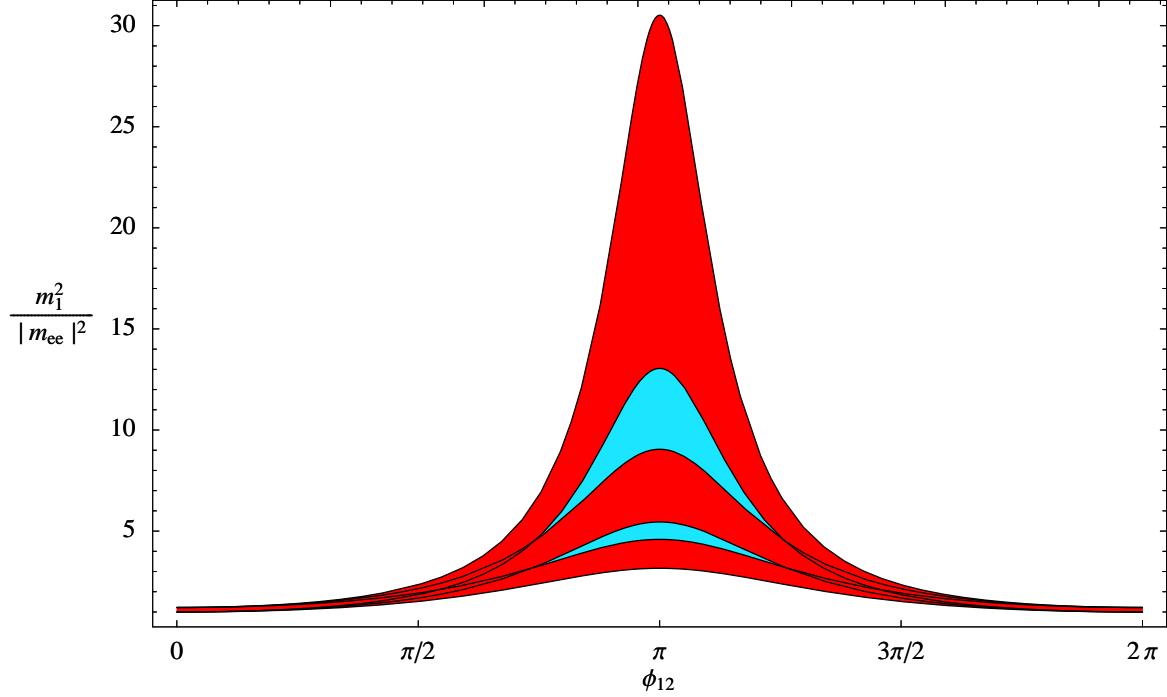


Figure 2: As Fig. 1, but with  $3\sigma$  limits on  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ ,  $\Delta m_{12}^2$ ,  $\Delta m_{23}^2$ .

$$|m_{ee}| = \xi \cdot (0.24 - 0.58 \text{ eV}) \quad [3\sigma]. \quad (9)$$

Here  $\xi = \mathcal{M}^{SMK}/\mathcal{M}^{(0\nu)}$  denotes the normalization to the NME  $\mathcal{M}^{SMK} = 4.2$ , calculated in the pn-QRPA model of [8]. While the initial claim caused a critical debate [12] and was not confirmed by an independent analysis of the data [13], several of these issues have been clarified in [14]. Remaining criticisms concern the exact peak position in the energy spectrum and the relative strength of measured background lines, which could suggest, that the observed signal is due to an unidentified background line or that the statistical significance of the signal is overestimated [15]. In any case, we feel motivated to take the evidence claim at face value and discuss possible consequences, although we stress that an independent test of the claimed evidence is essential, if possible with a different double beta emitter isotope. Such a test could be realized by the recently started CUORICINO [16] and NEMO experiments [17] and the recent MPI proposal [18] which revived the GENIUS proposal of the Heidelberg group [19].

Any conclusions about relations of the absolute neutrino mass  $m_1$  and the double beta decay observable  $m_{ee}$  depend crucially on the magnitude of the calculated NME. Typically the uncertainty of such calculations has been estimated to be a factor 2-3, assumed around a given central value such as the calculation in [8], i.e.  $\xi \in [0.5, 2]$ . In the following we

will argue in favor of a more stringent *upper* bound on  $\xi$  and that it constrains the allowed range of the CP Majorana phase  $\phi_{12}$ . In Table 1 a scan of all the available matrix element calculations has been performed. Most of the used models are based on the proton-neutron quasiparticle random-phase approximation (pnQRPA), like the renormalized pnQRPA, denoted by RQRPA in the table, the self-consistent pnQRPA (SQRPA), the self-consistent RQRPA (SRQRPA), and the fully self-consistent RQRPA (full-RQRPA). In addition, the pnQRPA has been improved by performing a particle-number projection on it in Ref. [20]. This theory has been denoted by projected pnQRPA in the table. The line with pnQRPA + pn pairing in the table denotes a theory where proton-neutron pairing has been added to the RQRPA framework.

In these calculations various sizes of the proton and neutron single-particle valence spaces have been used. They range from rather modest to very extensive single-particle bases. Also, the single-particle energies have been obtained either from the experimental data, or, more frequently, from a Coulomb-corrected phenomenological Woods–Saxon potential where the parameters have been adjusted to reproduce spectroscopic properties of nuclei close to the beta-stability line. In addition, in some calculations the Woods–Saxon single-particle energies have been varied close to the proton and neutron Fermi levels to reproduce low-energy spectra of the neighboring nuclei with odd number of protons or neutrons. Hence, remarkably diversified starting points have been used for the calculations.

Some nuclear matrix elements of this table can be discarded due to various deficiencies in the theoretical frameworks used to evaluate them. This concerns the shell-model matrix element  $\mathcal{M}^{(0\nu)} = 5.00$  of Haxton and Stephenson [21], who used the weak-coupling approximation in evaluation of it. This is quite a rough approximation, and the more recent matrix element  $\mathcal{M}^{(0\nu)} = 1.74$ , obtained by performing a large-scale shell-model calculation with realistic two-body forces, should be more reliable, although some doubts concerning the adequacy of the size of the used single-particle basis have been voiced. The reliability of the pnQRPA calculation including the proton-neutron pairing has been questioned due to the way the pairing is introduced to the theory. One can ignore the corresponding matrix element if one wants, without changing our final conclusions concerning the upper limit of the computed NME. The largest matrix element was calculated by Tomoda et al. in [22] by using a quasiparticle mean-field based VAMPIR approach with particle-number and angular-momentum projections included. The shortcoming of this approach is that it does not include the proton-neutron interaction in its framework, being essential in description of charge-changing nuclear transitions, which occur also in the double beta decay.

The above considerations lead to the range

$$0.59 \geq \mathcal{M}^{(0\nu)} \geq 4.59 \quad (10)$$

for the acceptable nuclear matrix elements. Since the upper limit of the above range comes from a pnQRPA calculation, one may ask how does the “ $g_{pp}$  problem” of the pnQRPA affect this value. This problem concerns the calculated matrix element of the two-neutrino double beta decay  $\mathcal{M}^{(2\nu)}$ , which turns out to depend strongly on the parameter  $g_{pp}$ , used as a scaling parameter of the particle-particle part of the proton-neutron two-body interaction [23, 24]. However, while the uncertainty in  $g_{pp}$  affects the *lower bound* on NME calculations dramatically ( $\mathcal{M}^{(2\nu)}$  can even become zero for a large value of  $g_{pp}$ ) towards lower values of  $g_{pp}$  the value for the NME enters a plateau, making the *upper bound* more stable against variations in  $g_{pp}$ . Moreover, even though the NME corresponding to the two-neutrino mode depends strongly on  $g_{pp}$  within its physical range, the NME corresponding to the neutrinoless mode depends only very weakly on this parameter. This can be clearly seen in Figs. 1 and 2 of Ref. [20], where the relevant double Gamow–Teller and double Fermi matrix elements have been plotted as functions of  $g_{pp}$  for the pnQRPA and projected pnQRPA calculations of the  $^{76}\text{Ge}$  double beta decay. The variation of these matrix elements around the physical value of  $g_{pp} \simeq 1$  is less than 20 per cent. Adding an uncertainty of 20 per cent to the above range of acceptable values of NMEs leads us to the upper limit

$$\mathcal{M}^{(0\nu)} < 5.5 \quad (11)$$

of the NME.

Consequently, the limits (7)–(9) read as

$$|m_{ee}| > 0.30 \text{ eV} \quad [1\sigma], \quad (12)$$

$$|m_{ee}| > 0.24 \text{ eV} \quad [2\sigma], \quad (13)$$

$$|m_{ee}| > 0.18 \text{ eV} \quad [3\sigma]. \quad (14)$$

These *lower* bounds on  $m_{ee}$  have to be compared to the most stringent *upper* bounds on the absolute neutrino mass scale,  $m_1$ , which are presently provided by data on cosmological structure formation. According to Big Bang cosmology, the masses of nonrelativistic neutrinos are related to the neutrino fraction of the closure density by  $\sum_i m_i = 40 \Omega_\nu h_{65}^2 \text{ eV}$ , where  $h_{65}$  is the present Hubble parameter in units of 65 km/(s Mpc). In the currently favored  $\Lambda$ CDM cosmology with a non-vanishing cosmological constant  $\Lambda$ , there is scant room left for the neutrino component. The free-streaming relativistic neutrinos suppress the growth

NME	Theory	References
5.00,1.74	Shell model	[21, 25]
1.53-4.59	pnQRPA	[8, 20, 26–33]
1.50	pnQRPA+ pn pairing	[28]
3.45	projected pnQRPA	[20]
6.76	VAMPIR	[22]
1.87-2.81	RQRPA	[32–35]
0.59-0.65	SRQRPA	[32]
2.40	full-RQRPA	[33]
3.21	SQRPA	[33]

Table 1: Compilation of calculated nuclear matrix elements for the neutrinoless double beta decay of  $^{76}\text{Ge}$ . The first column gives the value(s) of the NME, the second column the theory used to evaluate the NME, and the last column the works where the quoted theory was used to evaluate the NME.

of fluctuations on scales below the horizon (approximately the Hubble size  $c/H(z)$ ) until they become nonrelativistic at redshifts  $z \sim m_j/3T_0 \sim 1000$  ( $m_j/\text{eV}$ ).

Recent limits, obtained by combining CMB measurements with data on the large scale structure of the universe, imply an upper bound on the sum of the three neutrino mass eigenstates [36],

$$\sum_i m_i < 0.42 - 1.80 \text{ eV} \quad [2\sigma]. \quad (15)$$

The exact cosmological bound depends on the data and specific priors used in the analysis: The weakest bound utilizes only data from WMAP and the Sloan Digital Sky Survey. In particular, limits utilizing the Lyman- $\alpha$  forest, the absorption observed in quasar spectra by neutral hydrogen in the intergalactic medium, provide more stringent bounds [37]

$$\sum_i m_i < 0.42 - 0.69 \text{ eV} \quad [2\sigma], \quad (16)$$

as compared to the data sets without the Lyman- $\alpha$  forest [38],

$$\sum_i m_i < 0.6 - 1.8 \text{ eV} \quad [2\sigma]. \quad (17)$$

Since the effects of possible systematics in this data set need still to be explored further, both observationally and theoretically, each set of analyses should be discussed here. Within the present decade, the combination of SDSS data with CMB data of the PLANCK satellite

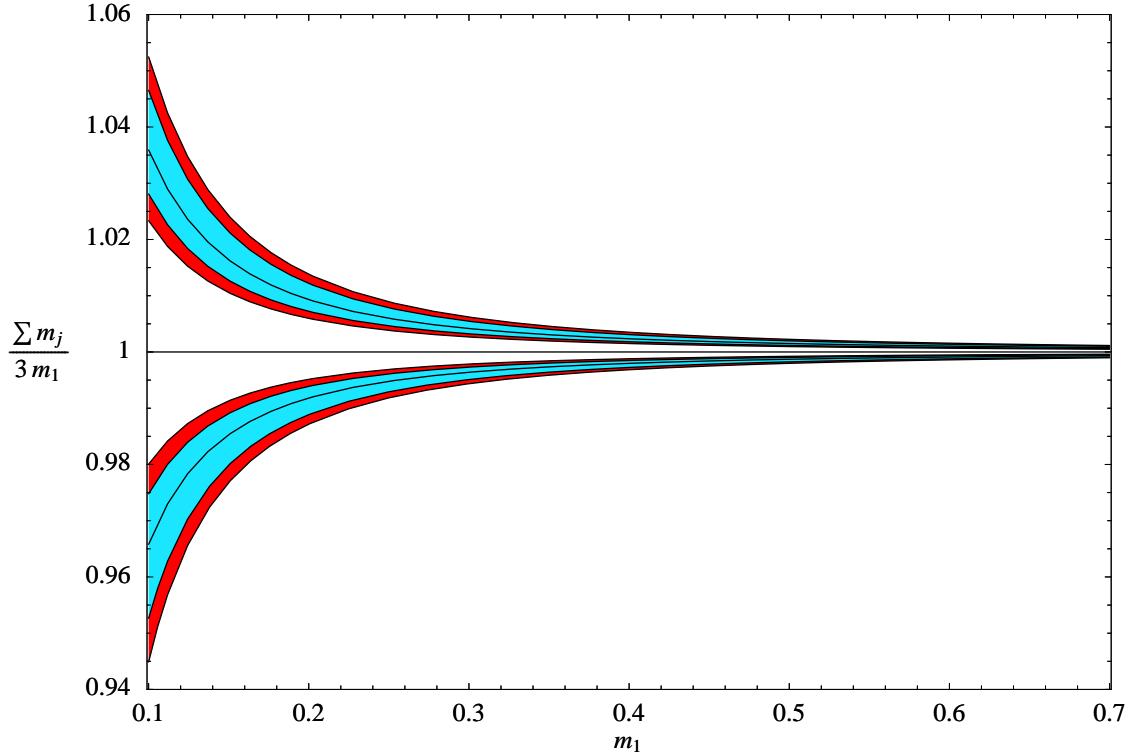


Figure 3: Relation of the cosmologically relevant sum of neutrino masses,  $\sum_i m_i$  and the lightest neutrino mass  $m_1$ . The upper and lower branches correspond to normal and inverse hierarchy, respectively. The light/blue and dark/red bands indicate the  $2\sigma$  and  $3\sigma$  range of  $\Delta m_{12}^2$  and  $\Delta m_{23}^2$ , while the central line marks the best fit.

will obtain a  $2\sigma$  detection threshold on  $\sum_i m_i$  close to 0.1-0.2 eV [36, 39]. Fig. 3 shows the relation of the sum of neutrino masses with  $m_1$ ,

$$\sum_i m_i = m_1 \left( 1 + \sqrt{1 + \frac{\Delta m_{12}^2}{m_1^2}} + \sqrt{1 + \frac{\Delta m_{12}^2}{m_1^2} \pm \frac{\Delta m_{23}^2}{m_1^2}} \right), \quad (18)$$

for normal and inverse hierarchy in the upper and lower panel, respectively. The different curves indicate the best-fit and upper and lower  $2\sigma$  and  $3\sigma$  ranges.

Combining the resulting bound on  $m_1$  with the range for the effective mass  $m_{ee}$  given in [10], one obtains:

$$m_1^2 / |m_{ee}|^2 < 0.36 - 0.93 \ (0.64 - 1.7) \quad \text{at} \quad 2\sigma \ (3\sigma) \quad (19)$$

for data sets using the Ly- $\alpha$  forest and

$$m_1^2 / |m_{ee}|^2 < 0.71 - 6.3 \ (1.3 - 11.1) \quad \text{at} \quad 2\sigma \ (3\sigma) \quad (20)$$

without the Ly- $\alpha$  forest. It is obvious, that the  $2\sigma$  range for the double beta decay observable is in conflict with all cosmological fits including the Ly- $\alpha$  forest and with some without the Ly- $\alpha$  forest. This may indicate that either the double beta decay signal is due to a statistical fluctuation or due to a mechanism involving exchange of other particles besides light massive Majorana neutrinos. Examples for the latter case include, e.g. sparticles in  $R$ -parity violating supersymmetry, leptoquarks, or right-handed neutrinos and  $W$  bosons (for an overview see [40]). Alternatively, the cosmological neutrino mass bound may not be applicable, e.g. by introducing broken scale-invariance in the primordial power spectrum [41], or due to fast decays of the relic neutrino background [42]. The  $3\sigma$  range for  $m_{ee}$ , however, is still compatible with most of the cosmological bounds although in most cases it is smaller than the minimum value,  $m_1^2/|m_{ee}|^2 = 3.81$  for  $\phi_{12} = \pi$ . If a value  $1 < m_1^2/|m_{ee}|^2 < 3.81$  will be confirmed in future cosmological data fits or in the upcoming tritium beta decay spectrometer KATRIN [43], Majorana CP phases around  $\phi_{12} = \pi$  can be excluded.

In conclusion, we discussed upper bounds on nuclear matrix elements and their implications for the Majorana CP phase  $\phi_{12}$ , when the recent evidence claim for neutrinoless double beta decay and the cosmological neutrino mass bound are combined. We deduced that for a combination of  $2\sigma$  experimental limits in most analyses the mass mechanism interpretation of the double beta decay evidence is incompatible with the cosmological neutrino mass bound. On the other hand, the range of the Majorana phase  $\phi_{12}$  can be constrained, when combining  $3\sigma$  experimental limits with reasonable upper bounds for the nuclear matrix elements. Assuming CP conservation, the CP phase factors  $\exp(i\phi_{ij})$  are reduced to CP parities  $\eta_{ij} = \pm 1$ . In this case the neutrino CP parity is fixed to  $\eta_{12} = +1$ .

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